Experimental Comparison of High Duty Cycle and Pulsed Active Sonars in a Littoral Environment

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Award Number: N00014-14-1-0226

LONG-TERM GOALS

To determine if near-continuous target detection obtained from using high duty cycle sonar provides improved performance over conventional pulsed active sonar, in a littoral environment.

OBJECTIVES

Military sonars must detect, localize, classify, and track submarine threats from distances safely outside their circle of attack. However, conventional pulsed active sonars (PAS) have duty cycles on the order of one percent which means that 99% of the time, the track is out of date. In contrast, high duty cycle sonars (HDC) have duty cycles approaching 100% which enable near-continuous updates to the track. If one can overcome technical challenges such as the high dynamic range required by the receiver, then HDC should significantly improve tracking performance in the free-field environment that one encounters (approximately) in the deep ocean; however, improvements in tracking performance in shallow water are not assured since both targets and clutter will be tracked continuously and HDC may increase false tracks to an unacceptably high level – essentially continuously tracking the clutter. Theoretical predictions of performance are challenging since the reverberation background for shallow water HDC has not been accurately modeled. To compare performance of HDC with conventional PAS in the littorals, a set of experiments were conducted as part of the Target and Reverberation Experiment (TREX) in spring 2013. This was the first scientifically controlled experiment conducted in the littorals to compare the environmental effects on these two approaches to active sonar. In this project the data from TREX will be analyzed to provide a quantitative comparison of the impact of the environment on the two techniques.

APPROACH

This project will be carried out primarily by the PI, Dr. Paul C. Hines at Dalhousie University's Dept. of Electrical and Computer Engineering. Additional research support will be provided by senior undergraduate research assistants and/or graduate students. TREX was conducted in approximately 20 m of water approximately 1 nmi off the coast of Panama City, FL. During TREX, comparative measurements of tracking and classification were made using HDC and PAS signals in a littoral

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2014**	2. REPORT TYPE	3. DATES COVERED **00-00-2014 to 00-00-2014**

4. TITLE AND SUBTITLE **Experimental Comparison of High Duty Cycle and Pulsed Active Sonars in a Littoral Environment**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Dalhousie University,Dept. of Electrical and Computer Engineering,5269 Morris Street, MA Bldg., Room 200,Halifax, Nova Scotia B3H 4R2,**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**15**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

environment[1]. This was the first scientifically controlled experiment conducted in the littorals to compare the environmental effects on these two approaches to active sonar. A series of metrics (eg. number of detections, matched-filter gain, false alarm rates, track purity, track latency, etc.) will be used to quantify detection, classification, localization, and tracking (DCLT) performance using the two sonar methods. The data are greatly enhanced by supporting environmental measurements made by DRDC and other TREX participants [1].

In the primary experiment, RV SHARP was fixed in a four-point mooring with an active sonar consisting of an ITC 2015 transmitter and the FORA horizontal line array receiver. CFAV QUEST towed an echo-repeater (ER) to act as a surrogate target along one of two 5 nmi long tracks, each of which started at the safe-standoff distance from SHARP (see Figure 1). Track 1 (referred to as the *reverberation track*) ran parallel to the shore at approximately 129°T; track 2 (referred to as the *clutter track*) ran offshore at approximately 240°T. The speed of advance for all runs was nominally 5 knots (on gas turbine to reduce self noise). Both the HDC and PAS pulses were linear FM (LFM) swept from 1800-2700 Hz with a pulse repetition rate of 20 seconds. The PAS pulse length was 0.5 s (2.5% duty cycle) whereas the HDC pulse was 18 s (90% duty cycle). The experiment was designed so that both pulses contained equal energy whenever possible; the HDC source level was 182 dB re 1µPa@1 m and the PAS was 197.6 dB re 1µPa@1 m.

Figure 1: Map of the TREX site showing QUEST GPS (blue lines) marking the run evolution for some of the reverberation and clutter track runs (see text for more detail).

A significant technical challenge of this experiment is that a conventional ER usually introduces a time-delay in the echo transmission to prevent its acoustic output from feeding back into the ER's receiver during pulse reception; however, introducing a simple time delay is not possible for an HDC pulse since by definition, HDC is nearly always transmitting. The innovate design of DRDC's SmartER used during TREX overcame this major hurdle. The experimental approach taken was to employ several techniques of increasing complexity; the simplest ensuring a basic comparison between HDC and PAS, and the most complex providing the most realistic comparison (in the absence of a real

1 Note that comparison of HDC and PAS is just one of several experimental objectives of TREX. Please refer to Ref. [1] for an overview of the experimental goals.

target) but at the cost of higher technical risk. A description of these techniques as well as additional details on the experiment are provided in [2].

WORK COMPLETED

The focus of the effort during FY 2014 has been as follows:

1. Data Quality Assurance: The project began by performing an overview of the HDC-PAS experiments to insure the data is of high quality.
2. Began a detailed analysis of a subset of the data to examine signal coherence of a pulse with a high time-bandwidth product.

A variety of runs were conducted during the trial. Controlled variables included the pulse type, echo-repeater mode and gain, and track choice. These variables were changed to test different situations and to experiment with what parameters would be most effective. Uncontrolled variables such as wind speed, sea state, ambient noise level, and local ship traffic were also present due to the nature of large scale field trials. During each run, the following types of data were recorded:

- Raw acoustic data captured in FORA on its triplet (cardioid) array module. The module consisted of 78 hydrophone triplets, each arranged in a equilateral triangle. Only the aft 48 triplets were operational at the time of the trials. The spacing between triplets is 0.2 meters providing a nominal half-wavelength spacing at 3750 Hz.
- Positional data for the R/V Hugh R. Sharp in FORA's non-acoustic (NAS) files although Sharp was stationary for all experiments. The source and receiver array positions were calculated using the cable scope and heading from Sharp's GPS position.
- Positional data for QUEST in DRDC NADAS format. The SmartER's position was extrapolated from QUEST's position using the cable scope and ship heading.
- Environmental data including sound speed profile, seabed composition, wind speed and wave height.

A summary of the run conditions and equipment configuration, along with an assessment of their suitability for HDC-PAS comparison is showed in Table I, which has been inserted at the end of the report due to its size. Initial quality assurance (QA) of the acoustic data was conducted by monitoring the time-series signal of the direct blast received on FORA (to ensure the signals weren't clipped) as well as monitoring signals received and re-transmitted from the SmartER to ensure the there was sufficient SNR. Within 12 hours of completing each run, a more detailed QA was conducted on the acoustic data collected on FORA[2]. First, the times-series data were filtered and down-sampled and demodulated to a complex time series. The complex time-series data were formed into 157 sinusoidally-spaced beams with beam 0 corresponding to forward endfire. Cardioids formed using the 48 triplets provided a non-ambiguous array with left-right signal rejection. Then the beamformed data were matched-filtered. The matched-filtered data was used for QA. These data were used to generate spectrograms, ambient noise and reverberation decay plots, and clutter images, all of which helped

[2] This was the first available window of time for processing the data since the raw acoustic data was delivered to QUEST after completing that day's HDC-PAS experiments.

assess data quality and highlight the effects of adjusting experimental parameters. Perhaps the most useful of these for QA were the clutter images which provided a rapid visual assessment to estimate SNR, identify at what range the transition from reverberation-limited to ambient-noise limited background occurred, and periods during which excessive noise from local boat traffic corrupted the data; these images, coupled with the wave-height data collected by collaborators from APL-UW, wind-speed data from anemometers on QUEST, and wave height estimates from shipboard sensors on QUEST helped identify which runs would be selected for detailed analysis.

The goal of the HDC-PAS component of TREX is to compare sonar performance for the two methods and the work in this project focuses on two investigations: In the first we note that although the HDC-PAS experiments used equal energy and bandwidth, the time-bandwidth product of the HDC pulse is significantly larger, owing to its longer pulse duration. This could lead to significant loss of processing gain out of the matched filter relative to PAS. The TREX data will be used to quantify the relative gain of HDC and PAS using echoes from DRDC's Passive Acoustic Target System (PATS) which was deployed approximately 3 km away from the SHARP, slightly north of the reverberation track. This provides a so-called *fixed-fixed* [3] measurement to compare the processing gain for HDC and PAS directly, and examine whether the acoustic channel can support very large time-bandwidth products for different environmental conditions. In the second, the SmartER and QUEST echoes are used to investigate HDC-PAS tracker performance. HDC provides the possibility of continuous tracking by dividing the pulse into a series of sub-bands which effectively splits the signal energy that is available for the (single) PAS detection; therefore, to maintain the PAS detection performance in HDC, one must reduce the detection threshold and increase the false alarm rate (FAR). In this phase these trade offs will be examined to compare HDC and PAS performance from detector through the tracker. A series of metrics such as number of detections, false alarm rates, track purity, and track latency will be used to quantify performance using the two sonar methods. In the following section, some general results from the initial analysis, and the analysis plan for the coming year are presented.

RESULTS

Given the amount of data collected during the HDC-PAS component of TREX, a subset of runs were identified for extended analysis. The comparison should be performed for cases where both the controlled and uncontrolled variables (outlined in the previous section) were similar. Using the same data for all the analysis will reduced the workload, but the constraints on the tracker data are more limiting than the fixed-fixed analysis; therefore, the more-limiting criteria were used to select HDC-PAS run pairs as follows:

- QUEST should travel along the same track, in the same direction for HDC-PAS run pairs.
- Only one pulse type was be used for the entire run to obtain sufficient echo statistics.
- Runs with excessive boat traffic were avoided to prevent lost detection on low SNR echoes from the SmartER.
- Data should have been collected using the same SmartER target strength and it should be set such that detections are made but provide some "challenge" for the detector-tracker (this proved to be a particularly challenging criteria throughout the experiment).

[3] A fixed-fixed measurement implies that the source and receiver, or in this case, the active sonar and target, are both stationary so that one can assess the impact of the channel on acoustic performance without accounting for sonar or target motion.

- Run pairs should have similar weather conditions and done within a short time of one another.

Finally, to assess the impact of environmental factors on HDC-PAS, two distinct run pairs were required; one pair collected during calm weather, and one collected during rough weather to see if there is a relative change in performance between HDC and PAS. It wasn't possible to satisfy all these conditions due to competing experimental priorities. Nonetheless, the one most closely matching these criteria are runs 80 and 82 (calm weather) and runs 100 and 102 (rough weather) and are highlighted in green in Table 1. A second set of runs (84, 86 and 106, 110) are highlighted in yellow and provide an alternate (or additional) dataset should it be necessary. Figures 2a and 2b show the surface wave-height and wind speed during two 30 hour periods that encompass all eight runs. The start of each of the runs is marked with an arrow.

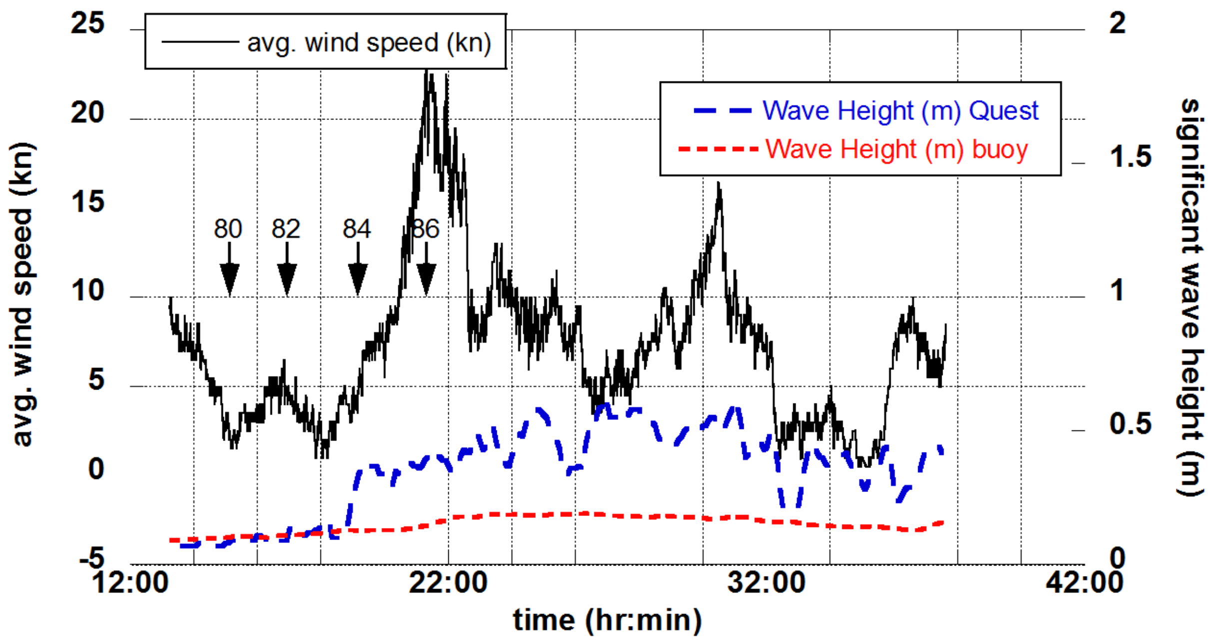

Figure 2a: Wave height measured by APL-UW wave buoy (blue long dash) and QUEST's downward-looking X-band TSK WM-2 wave-height meter (red short dash) and wind speed (solid black line), for a 30-hour period starting at 12:00 UTC on 10 May 2013. The lhs axis begins at -5 kn to separate the wind and wave curves.

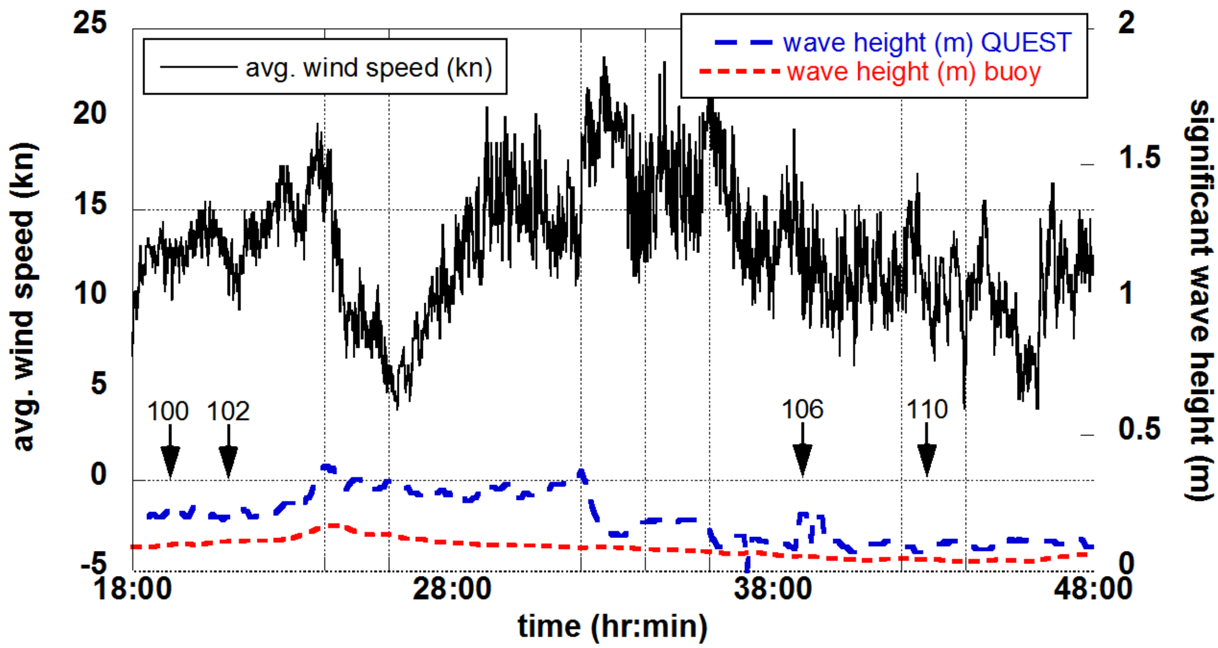

Figure 2b: Wave height measured by APL-UW wave buoy (blue long dash) and QUEST's downward-looking X-band TSK WM-2 wave-height meter (red short dash) and wind speed (solid black line), for a 30-hour period starting at 18:00 UTC on 12 May 2013. The lhs axis begins at -5 kn to separate the wind and wave curves.

The clutter image for HDC run 80 and the corresponding PAS run 82 are shown in Figures 3 and 4. The diagonal lines from lower left to upper right in the images are echoes from the SmartER (upper line) and QUEST's hull (middle and lower line). There are of course, multiple returns from QUEST's hull but the particulars of the clustering algorithm collapsed them into two distinct returns. The SmartER line appears dashed because alternate pings were echoed (See "ping pong" mode in Ref. 2). Run 80 was split into two 30 minute files which results in the black vertical band in the middle of the image. The vertical white bands in both images are "wash-out" from noisy water-craft in the area. The straight horizontal white lines are clutter from stationary objects. The diffuse horizontal line marked by the red arrow in Figure 3 is thought to be scatter from schooling fish. The clutter image for HDC run 100 and the corresponding PAS run 102 are shown in Figures 5 and 6. Many of the features are similar to Figures 3 and 4 but two items are worthy of note: First, QUEST executed a 360° elongated turn resulting in the curved track. The broadside highlight of QUEST is visible at the local maximum and local minimum in both figures; second, SmartER was run in "dual band" mode [2] which generates an echo for every ping, leading to twice the echo density relative to Figures 3 and 4.

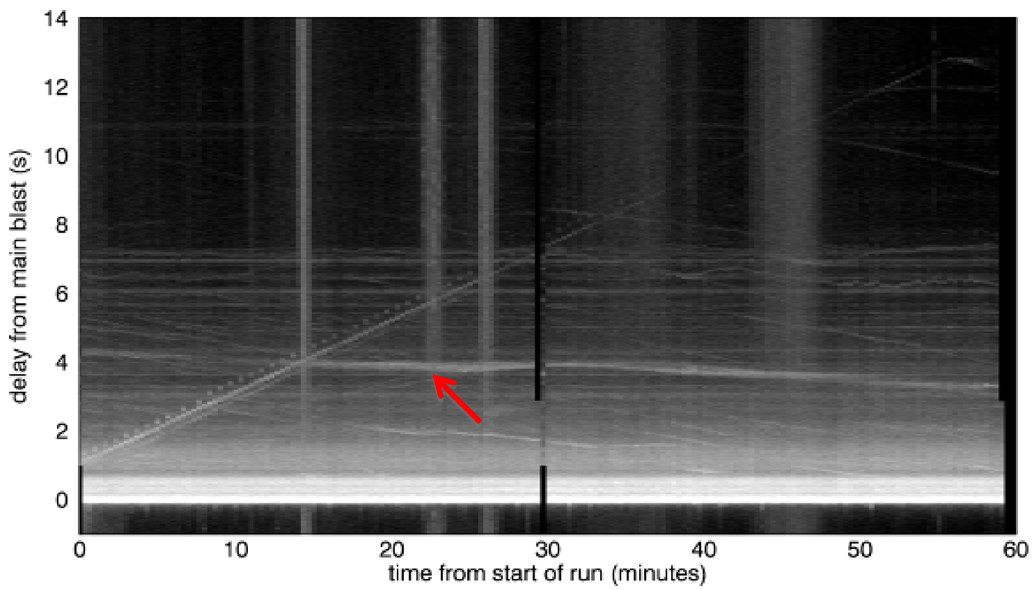

Figure 3: Clutter image of HDC run 80 for a single beam steered along the clutter track. The vertical axis is time in seconds after the main blast is received on FORA (referred to as "fast time"); the horizontal axis shows time during the entire run (referred to as "slow time"). See text for additional details.

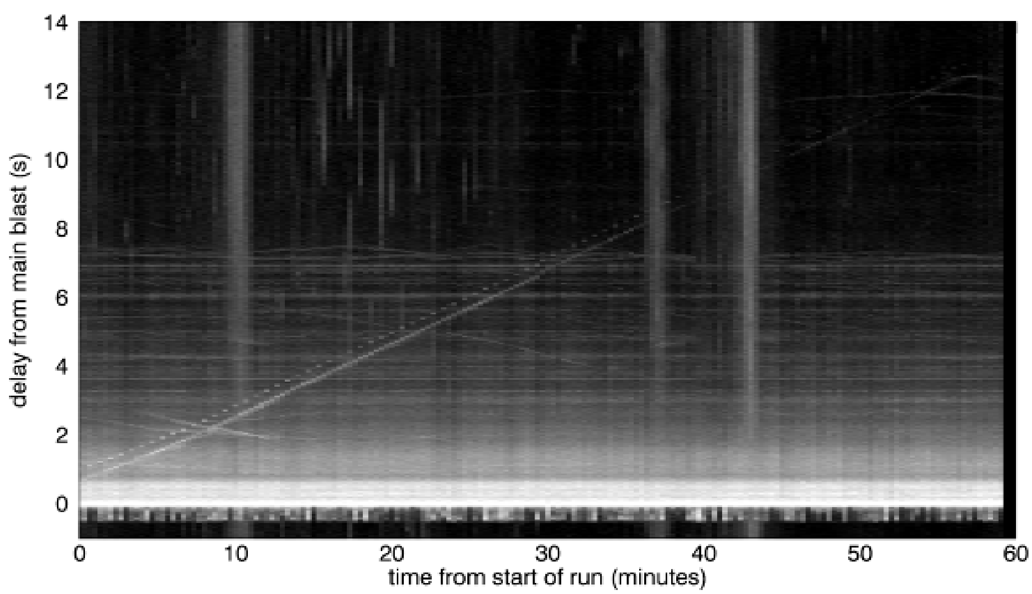

Figure 4: Clutter image of PAS run 82 for a single beam steered along the clutter track. See text for details.

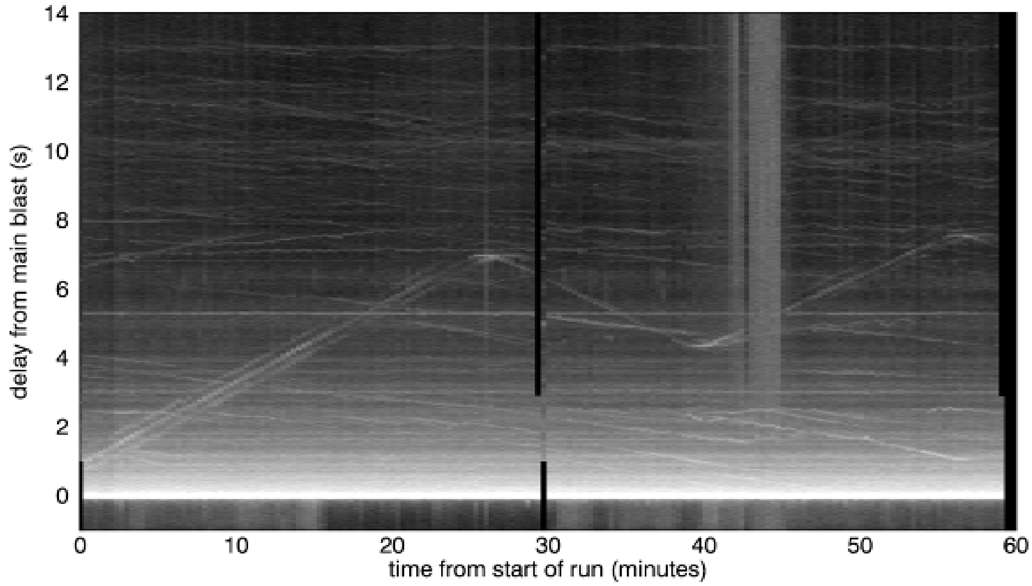

Figure 5: Clutter image of HDC run 100 for a single beam steered along the reverberation track. See text for details.

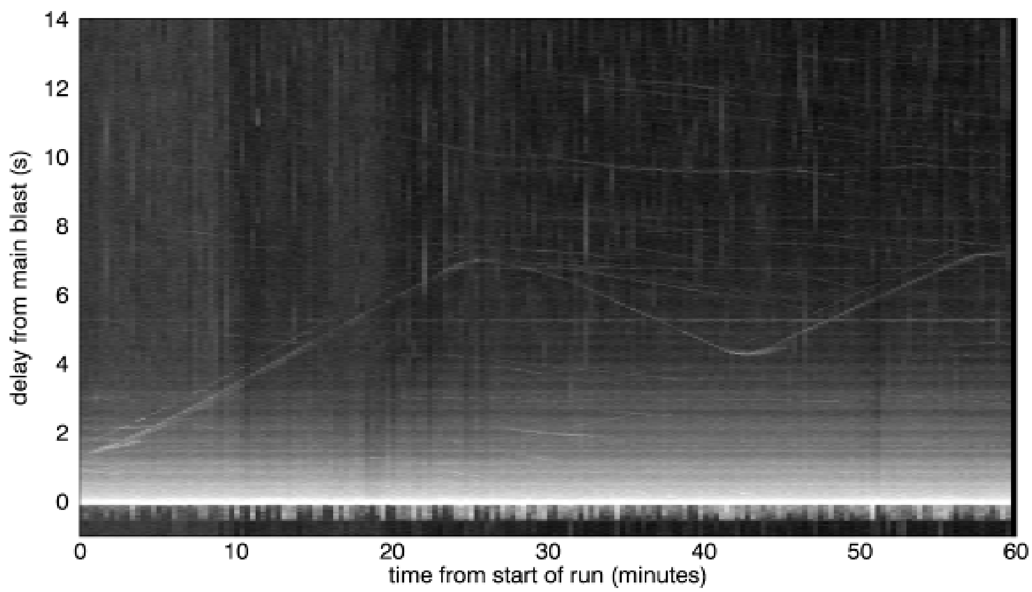

Figure 6: Clutter image of PAS run 102 for a single beam steered along the reverberation track. See text for details.

Figures 7 and 8 contains clutter image for runs 80 and 82, respectively, for beam 59 –the beam pointing directly at the PATS. The PATS echoes are seen as the green dots occurring at roughly t = 3.6 s. The tight clustering of the points (in fast time) is indicative of the stability of the PATS position. Overlaid on both figures, and corresponding to the right-hand vertical axis, are the PATS peak echo amplitude, the estimated reverberation level at the time of the echo, and the signal-to-reverberation ratio (SRR). In both runs, the peak amplitude of the echoes and the SRR remained fairly constant throughout the run, with the exception of a few periods where noise from local boat traffic corrupted the measurements. That said, the ping-to-ping variation in the PATS echo appears to be lower during

the HDC run. This is borne out when one computes the mean and variance of the PATS SRR for runs 80, 82, 100, and 102 as shown in Table 2. It is likely that the reduced variance results from the longer

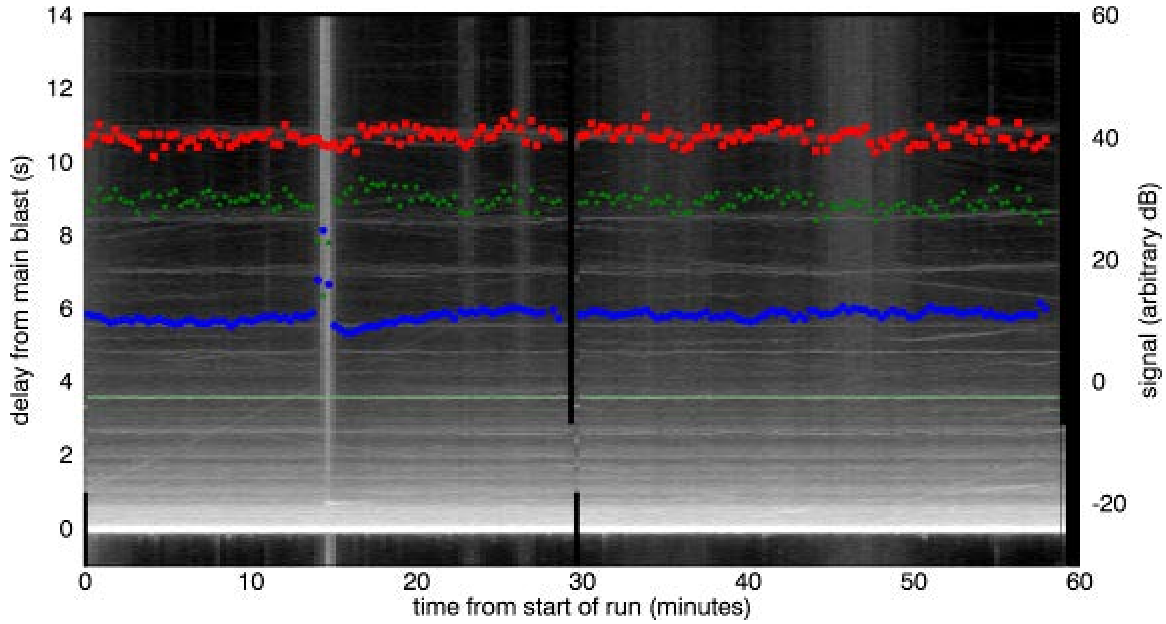

Figure 7: PATS echo statistics for run 80 overlaid on the HDC clutter image for beam 59. Red squares represent peak echo amplitude, blue circles represent mean reverberation, and green stars represent SRR. The vertical scale on the left hand side of the figure shows the time-after-reception of main-blast; the vertical scale on the right hand side gives the relative amplitudes of the echo statistics in decibels.

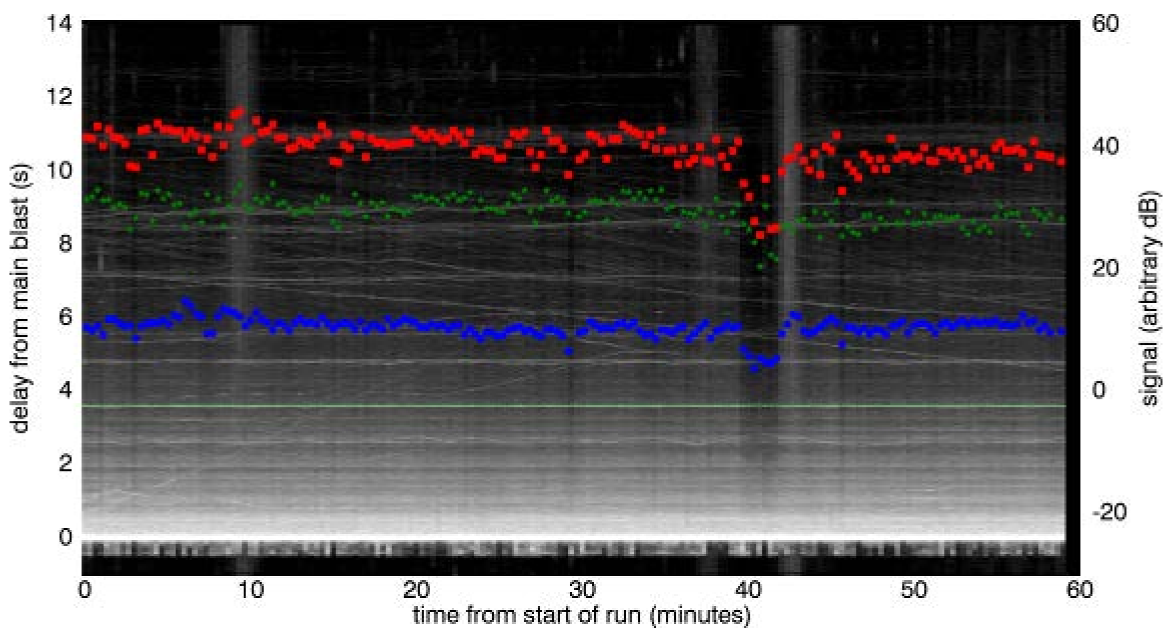

Figure 8: PAT echo statistics for run 82 overlaid on the PAS clutter image for beam 59. The display parameters are the same as for Figure 7.

averaging time of the HDC pulse. Each data point in the correlated time series encompasses data from a time-window equal in length to the replica waveform. Therefore, for HDC full-band correlated data is averaged 36 times longer than PAS. This makes the HDC processing less sensitive to short-term variations in the environment such as surface motion. One unexplained feature in the data is that the SRR is nearly 3 dB lower for PAS run 102 than for corresponding HDC run 100. This is counter-intuitive since one would anticipate that coherently-processing the smaller time-bandwidth PAS signal would come closer to reaching the theoretical limit than the HDC signal. It is worth noting that it was necessary to reduce the PAS source level by 3 dB for all dual-band SmartER runs because of the power limitations in the ITC 2015 source. That is to say, the HDC-PAS equal-energy approach had to be abandoned for those runs. However, the 3 dB drop in source level should only affect the SNR in ambient noise limit regions, not the SRR at reverberation-limited ranges.

Table 2: Signal-to-Reverberation (SRR) for four of the runs.

run	Mean (dB)	Variance (dB)
R80 (HDC)	29.4	1.9
R82 (PAS)	29.2	2.5
R100 (HDC)	26.9	1.9
R102 (PAS	24.2	3.2

Figure 9 shows a plot of the intensity time-series for beam 59 averaged over all 180 pings for runs 100 and 102. It appears that the reverberation is only 5-10 dB higher than the ambient noise background during the PAS run so the PATS echo may be arriving in the reverberation-limited to ambient-limited transition region. The plot also indicates that the reverberation is about 3 dB higher for HDC than for PAS. One should bear in mind that these are preliminary results and this will be investigated further. The most important observation is that the data appear to be of very high quality and will provide an excellent data set with which to compare HDC and PAS performance.

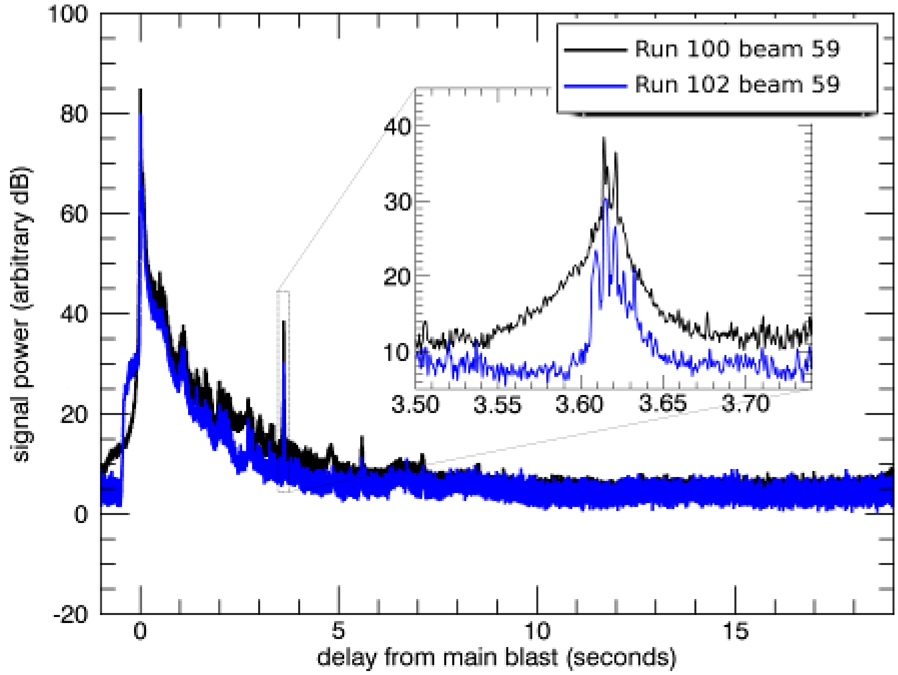

Figure 9: Match-filtered intensity time-series averaged over all pings for runs 100 and 102. The PATS echo is visible at approximately 3.6 seconds after the main-blast arrival. The inset shows a zoomed version of the echo.

The signal processing performance will be complemented by reverberation measurements and modeling by collaborators in the TREX trail. To support the reverberation modeling, DRDC's free-falling cone penetrometer was used to estimate seabed composition along the reverberation and clutter tracks. A summary of the results are presented in Figures 10 and 11 and show that penetration depth was significantly greater along the reverberation track. Measurements from the penetrometer were converted to the Roberson zone scale [3] shown at the right of the figures. A value of 7 indicates a sand/gravelly-sand bottom and 6 indicates sand/silty-sand.

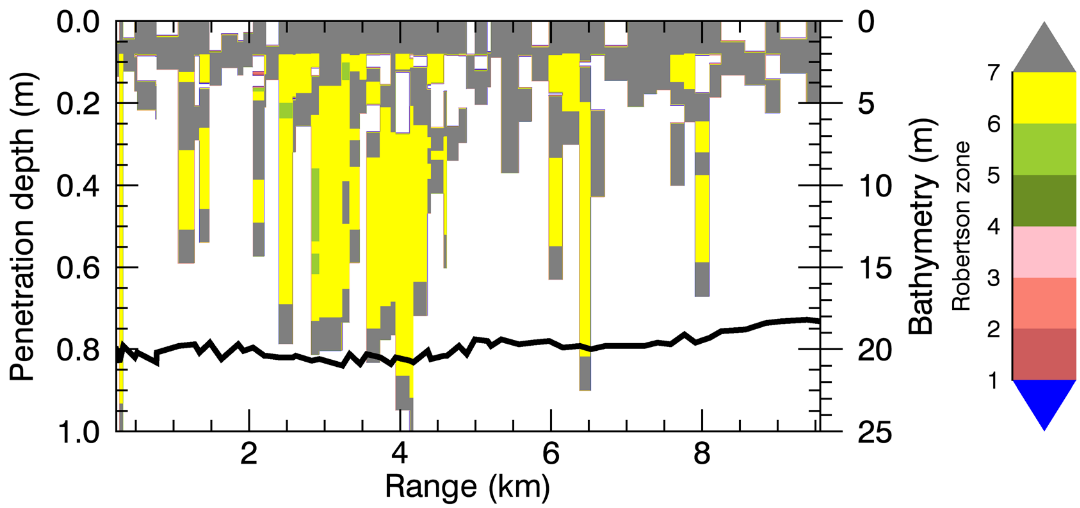

Figure 10: Robertson zone seabed composition extracted from DRDC's free-falling cone penetrometer measurements for reverberation track. Penetration depth is shown on lhs and bathymetry is shown on rhs.

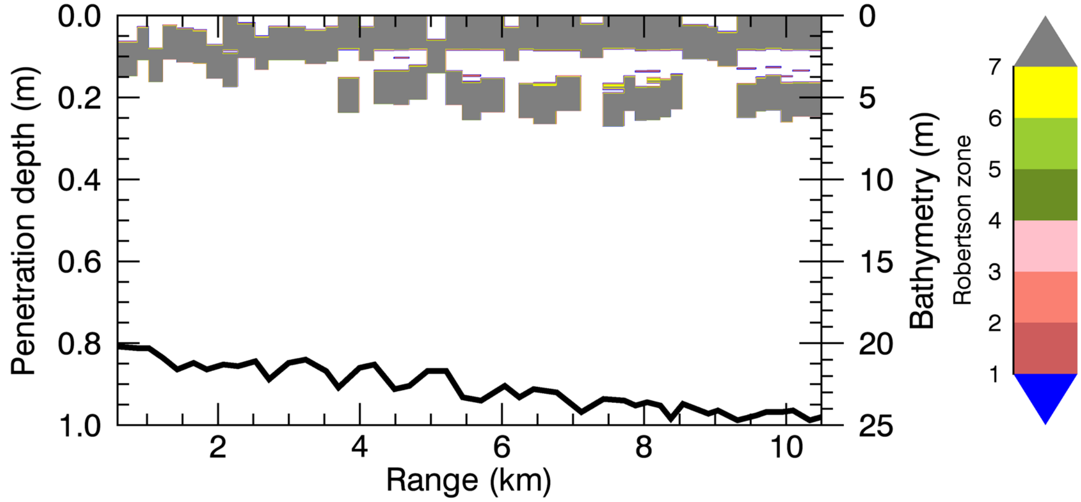

Figure 11: Robertson zone seabed composition extracted from DRDC's free-falling cone penetrometer measurements for clutter track. Penetration depth is shown on lhs and bathymetry is shown on rhs.

IMPACT/APPLICATIONS

Automated DCLT in support of anti-submarine warfare (ASW) is critically important to the US Navy; its importance will continue to increase as shrinking defense budgets translate to fewer ASW ships and smaller crew sizes. DCLT is particularly challenging in littorals where clutter (active sonar echoes from non-targets) causes unacceptable false alarm rates in classifiers and overloads automated tracking algorithms by generating too many false tracks. Furthermore, High Duty Cycle sonar is rapidly becoming a high profile topic as both the US and Canada integrate this technology into their respective fleets. HDC offers some exciting possibilities in ASW but its performance in high clutter (eg. littoral) environments has not been scientifically verified, and is by no means assured. The analysis proposed here will provide a scientifically controlled side-by-side comparison of HDC and PAS performance for DCLT in a littoral environment. As well as increasing our knowledge base on the subject, it will provide a dataset which will anticipate future questions from the operational community as HDC is employed. Predicting uncertainly in transmission loss and reverberation based on environmental variability will enable exploitation of environmental knowledge to identify the best window of opportunity to execute military operations and provide tactical guidance for optimal deployment of ASW sonars and supporting environmental measurements.

RELATED PROJECTS

A multi-national joint research project (MN-JRP) lead by the Centre for Maritime Research and Experimentation (formerly NURC) is in the final stages of approval. This project will leverage the knowledge and lessons learned from the TREX experiment (and the subsequent data analysis) to conduct dedicated shallow water HDC experimentation, in an operationally-relevant environment, to further assess HDC ASW performance in the littorals. The PI as well as several other members of the TREX experiment are involved in the development of this project. This MN-JRP will study the efficacy of HDC in shallow water for target detection, localization, tracking, and classification compared to the conventional PAS baseline. Particular attention will be paid to quantifying the impact

of the shallow water environment on HDC performance. The MN-JRP is built around the concept of performing one or two ASW experiments with the NRV Alliance and a diesel-electric submarine target. While experimentation dedicated to HDC data collection is planned, the MN-JRP will also seek to exploit NATO exercises where possible. The first experiment would be in 2015.
This research will benefit from DRDC Atlantic's Force ASW Program which is using the TREX data to support its work in classification and tracking. The PI is collaborating closely with the DRDC team working on the TREX analysis.

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2. Paul C. Hines, "Experimental Comparison of Continuous Active and Pulsed Active Sonars in Littoral Waters," Proceedings: 1st Conference on Underwater Acoustic, Corfu, Greece, June 2013.
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1. Stefan M. Murphy, Paul C Hines, and Kevin Dunphy, "Classifying Continuous Active Sonar Echoes for Target Recognition ," Proceedings: 2nd Conference on Underwater Acoustics, Rhodes Greece, June 2014. [published].
2. Paul C. Hines, "Experimental Comparison of Continuous Active and Pulsed Active Sonars in Littoral Waters," Proceedings: 1st Conference on Underwater Acoustic, Corfu, Greece, June 2013. [published].

Table 1: Summary of TREX HDC-PAS experimental runs using the equal-energy linear FM pulses described in the text. Outbound runs are preferred because it is easier to isolate echoes from QUEST and the ER. The phrase "paperclip loop" is a visually descriptive term for runs during which Quest's track included a 360° turn in roughly the shape of a paperclip to "challenge" tracking algorithms. The phrase "corresponding run" in the comments column implies HDC-PAS runs on the same track, the same direction (inbound or outbound), and the same ER mode and gain settings. These runs are best suited for a direct comparison of the performance. Runs highlighted in green were selected for detailed analysis and runs highlighted in yellow were identified as alternate candidates for detailed analysis. It should be noted that the PI also conducted runs using more complex HDC pulses for other ONR sponsored scientists but these are not reported on herein.

Run	UTC	dd/mm	Pulse	Mode	Gain (dB)	Track	Comments
63	14:10	05/08	HDC	Ping Pong	25	outbound, clutter track	ER gain set for high SNR detection; Corresponding PAS is run 65
64	15:30	05/08	HDC	Dual Band	25	inbound, clutter track	ER gain set for high SNR detection. Corresponding PAS is run 66
65	16:45	05/08	PAS	Ping Pong	25	outbound, clutter track	ER gain set for high SNR detection; Corresponding HDC is run 63
66	18:00	05/08	PAS	Dual Band	25	inbound, clutter track	ER gain set for high SNR detection. Corresponding HDC is run 64
67	20:10	05/08	PAS	Ping Pong	25	outbound, reverb track	ER gain set for high SNR detection. No corresponding HDC run.
73	17:00	05/09	HDC	Tracking Filter	25	outbound, reverb track	Advanced test ER mode. No corresponding HDC run.
77	21:00	05/09	PAS	Dual Band	25	outbound, reverb track	No corresponding HDC run.
80	*15:00*	*05/10*	*HDC*	*Ping Pong*	*0*	*outbound, clutter track*	*ER gain set for low SNR detection; Corresponding PAS is run 82; Low wind/wave conditions.*
82	*17:00*	*05/10*	*PAS*	*Ping Pong*	*0*	*outbound, clutter track*	*ER gain set for low SNR detection; Corresponding HDC is run 80; Low wind/wave conditions.*
84	19:00	05/10	HDC	Dual Band	0	outbound, reverb track	ER gain set for low SNR detection Corresponding PAS is run 86 which has similar wave heights but run 86 winds are 10 kn higher.

Run	UTC	dd/mm	Pulse	Mode	Gain (dB)	Track	Comments
86	21:00:00	05/10	PAS	Dual Band	0	outbound, reverb track	ER gain set for low SNR detection Corresponding HDC is run 84 which has similar wave heights but run 84 winds are 10 kn lower.
96	15:00:00	05/12	HDC	Tracking Filter	0	outbound, reverb track	Advanced test ER mode. No corresponding HDC run.
100	*19:00:00*	*05/12*	*HDC*	*Dual Band*	*5*	*outbound, reverb track paperclip loop*	*ER gain set for low SNR detection; Corresponding PAS is run 102; High wind/wave conditions.*
102	*21:00:00*	*05/12*	*PAS*	*Dual Band*	*5*	*outbound, reverb track paperclip loop*	*ER gain set for low SNR detection; Corresponding HDC is run 100; High wind/wave conditions.*
106	15:00:00	05/13	HDC	Dual Band	10	outbound, clutter track 360 turn	ER gain set for med SNR detection; Corresponding PAS is run 110 with similar wind/wave conditions.
110	19:00:00	05/13	PAS	Dual Band	10	outbound, clutter track 360° turn	ER gain set for med SNR detection; Corresponding HDC is run 106 with similar wind/wave conditions.
112	21:00:00	05/13	HDC	Dual Band	10	outbound, reverb track 360° turn	No corresponding PAS run (insufficient time).